Industry Workshop

November 26th, Toronto, ON

Materials and Manufacturing Ontario
Sheridan Science and Technology Park
Mississauga, Ontario

Modeling for "Green Manufacturing"

It is generally believed that the factors that will influence the adoption of new technologies in the manufacturing industry are environmental issues, cost and the application of computer simulation. Computer simulation of industrial processes–focussing on energy usage and GHG emissions–addresses environmental and cost issues by allowing optimization of materials and processing parameters. A paper presenting the key issues, importance and future of environmental issues in manufacturing: green manufacturing, is attached as Appendix A together with a glossary of "green engineering". Although the trends described are grounded mainly in the near term and describe all facets of life-cycle analysis-not just GHG emissions-the overview provides a good background to understanding the problems facing the "greening" of the manufacturing sector.

Total lifecycle analysis modelling, comprising environmentally conscious manufacturing, is essential to achieve long-term sustainable development. Manufacturing with lower energy use and material waste, more benign materials and processes, recyclable products and lower environmental burdens is a goal that can be met by analysing and integrating every step in the production chain.

Dr. George's Salloum's paper on "Process Modelling" illustrates how concurrent product and process development, one element of total lifecycle analysis, can be achieved through process modelling (Appendix B). There is a real need for this type of simulation that relies on comprehensive database information. In turn, the databases rely on generation of good experimental data. These data are required to verify any model.

The workshop participants addressed how and why modelling could be useful in providing a total process lifecycle analysis of GHG emissions in industrial processes. A flow chart was developed detailing the all the factors pertinent to lifecycle GHG emissions. The components of the flow model were established and a time line from 2000 to 2050 was established. In developing the model the participants discussed manufacturing technologies they felt would be important in the long-term. This discussion is reflected in Appendix C "Factory of the Future".

A Generic Model for Lifecycle Analysis of GHG Emissions

Powerful and high-speed computing in conjunction with finite element analysis software have created the opportunity for engineers to predict the performance of a proposed design without building an experimental prototype. This approach, if adopted in designing manufactured products, would allow quantification of GHG-emissions and energy-consumption throughout the total product lifecycle cycle. Armed with this information it should be possible to optimise the lifecycle as a whole to minimise GHGs and energy consumption. "Best fit" recommendations for every step in the production, usage, and disposal chain would result from the analysis.

Why Model GHG Lifecycle Emissions?

1. Modelling can be used to decrease GHG emissions in industrial processing. This implies:
   - reduced use of carbon
   - reduced energy usage/increased efficiency
   - CO_2 management
2. Modelling can be used to provide an integrated systems approach that incorporates lifecycle management of both design (including materials design) and process (i.e. it is not restricted to specific products, it also takes account of the total energy system).
3. Modelling is a **driver** for technology development and improvement.
4. Modelling will enable hazard prediction.
5. It costs too much not to model!

Prerequisites for good lifecycle analysis modelling

1. Good science and engineering is a necessity for development of a good model i.e. the model must be verifiable with accurate, real-world data.
2. Adequate emphasis should be placed on the biological, as well as the physical and chemical, sciences.
3. The perception of engineers as "problem solvers" in partnership with the social and the "hard", sciences should be enhanced.
4. A sizeable investment has to be made in public and traditional education that will enable acceptance of a total lifetime model approach to reducing GHG emissions.

A Generic Model for Lifecycle Analysis of GHG Emissions

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Large, Readily-Accessible Databases

- Web-based searchable databases should be available for materials, processes and products.
- On-going process that needs a great deal of maintenance

Energy Consumption Module

- Upstream (energy sources used for materials etc.) and downstream (energy used in product manufacture) energy usage paths will be considered. This will highlight energy efficiency problems/emissions over total product lifecycle-from mining the ore and in-service use to the final product.
- Companies should consider not only local but at-a-distance pollution/grid network/ alternative energy sources/societal needs. This implies relevant geographical data have to be included in the databases.
- Common energy values need to be developed for comparative purposes
- Group (sectoral) technology has to developed for this module
- Maintenance and support for end users is implicit

Part Processing Technologies

- Identification of the best part materials, fabrication and processing technology to minimize the energy input e.g. increased use of near net shape processes that yield complex parts with good dimensional tolerances and surface finish so that little or no secondary processing, e.g. machining, is required

Assembly/Joining Technologies

- Embedded artificial intelligence will allow remote part assembly, production and manufacturing.
- Fixtureless assembly and increased use of adhesives are likely in the 2030-2050 time frame.

Recyclability Module

- Separation/sorting technologies
- Collection mechanisms
- Requires need-based multi-applicational design software

Impact Analysis

- Knowledge of all parameters can determine total impact on the environment
  - hazards
  - economic
  - societal–health, resource usage
- Global understanding and acceptance of impact on health and resources has to be reached
- Codes on qualitative and societal impacts have to developed

Scientific Model Development

- Process modelling/planning
- Integration of model components
- Optimization of materials, process, energy system, assembly etc.
- Risk assessment
  - safety
  - ecological
  - economic
- Very friendly artificial intelligence interfaces for non-experts have to be developed

Refinement of Scientific Model

Preferred Attributes for

- Process
- Product
- Materials
- Energy system

Design Sensitivity Analysis

- Tools need to be developed –simple tools could be developed in a 5 year time frame, more robust tools will take 20 years to develop.

Change Process

- Technology gaps and barriers identified
- R & D projects/opportunities identified
- Investment to be obtained
- Government measures to be implemented
- Codes and standard, regulation development and implementation

The components/modules can be developed simultaneously if they are mutually independent, or sequentially if information from another component/ module is required as input

GHG Emission Lifecycle Analysis Model

- Graphical user-friendly interface/processing
- Easily identifies major GHG emission sources in process
- Optimizes process/materials etc. to minimize emissions
- Provides maintenance and support to end users

1. Energy Consumption Module

The parameters for upstream and downstream energy usage path for a particular product or process would be identified. The purpose would be to highlight energy efficiency problems/emissions over total product lifecycle i.e. from mining the ore, to in-service energy consumption of the product, to disposal of the final product. Through this analysis companies would be constrained to consider the implications not only of local pollution but also at-a-distance pollution created, for example, by the way an electrical utility produces the electricity it feeds into the grid. A discussion of hydrogen as a clean energy carrier was made by Prof. Ron Venter, University of Toronto and is attached as Appendix D. Alternative energy sources and societal needs would be identified. The integration of lifecycle analysis to development of new technologies and materials would provide a material and energy balance over the entire material lifecycle and it would enable the negative environmental impacts of products or processes to be minimised. It would require a complete analysis of each step in the manufacturing process. The energy used by in-service use of the product would be considered as a part of this analysis. To enable effective energy consumption measurement detailed materials, processes and product data are needed.

2. Part Processing Module

The most suitable materials and processing technologies (making and shaping) would be identified for part production. A detailed model of product/process integration for injection moulding, die casting, blow moulding and thermoforming is given in the paper by Georges Salloum, IMI, NRCC attached as Appendix B. Some examples of other energy efficient technologies that could be included in the database are given below.

Near-net-shape processes are environmentally friendly fabrication technologies. They can be tailored to produce the required properties and microstructure and substantially reduce the energy requirements and unit cost of a part by reducing machining, secondary processing, and material waste. Powder metallurgy, powder injection moulding, permanent mould casting, investment casting, lost foam casting, squeeze casting, die casting, semi-solid metal casting and forging, thixomoulding and rapid prototyping are all examples of current near-net-shape processes.

Hydroforming and tailor-welded blank formability represent energy efficient process advances in forming technology. Hydroforming is the application of a fluid against the surface of a workpiece to form a complex shape. The ability to form tailor-welded blanks consisting of various alloys, sheet metal gauges and/or sheet metal finishes has enabled reductions in energy consumption in metal forming processes.

Accurate materials and process data are essential to ensure material/process compatibility, process optimisation (minimised energy usage) and compliance with final product property specifications e.g. hardness, fracture toughness, fatigue and corrosion resistance etc.

3. Assembly/Joining Module

The most suitable assembly and joining technologies for manufacturing a particular product to consume minimum energy, and hence produce minimum GHG emissions would be identified in this module. Data on compatibility of material type, cross-sectional shape and thickness etc., available joining or assembly processes e.g. fixtureless assembly, adhesive bonding, welding techniques etc., and the energy used in these processes are crucial to identification of the "right" joining and assembly technologies.

Some of the characteristics of future manufacturing and assembly lines were addressed in the context of factories of the future -see Appendix C.

4. Recyclability Module

In the interests of conserving energy and minimising waste it will important to promote reuse and recycling. If a product cannot be reused then it should be disassembled, separated into those component parts that can be recycled to minimise the amount of waste. The objective of the recyclability module would be to use effective separation techniques and materials to maximise the recyclability fraction of the product and decrease the fraction for disposal in landfill etc.

Separation technologies are diverse and depend on the phase or phases to be separated. Separation can be carried out by mechanical, chemical, electromagnetic or biological means. Separation and purification of gases, water purification, separations of other sorts using liquids: membranes, pervaporation, absorption or supercritical fluid extraction, hydrometallurical separations, ion exchange membrane technology, dewatering, crystallisation or magnetic separation are examples of technologies that can be used. It should be mentioned that separation technologies also play an important part during processing. For examples membrane technology can be used for large-scale selective recovery of carbon dioxide from flue gases of fossil-fuel plants where it can be sequestered or converted to chemical products such as ethanol. It was felt that membrane separation in particular would become increasingly important in the long-term.

5. Impact Module

The effect of minimising energy usage and GHG emissions on health and safety, environmental degradation, the costs involved and implications for societal change are factored into the impact module.

6. Database requirements

The integration of lifecycle analysis to development of new technologies and materials provides a material and energy balance over the entire material lifecycle and it enables the negative environmental impacts of products or processes to be minimised. This requires a complete analysis of each of the steps of the manufacturing process.

Successful process optimisation for minimum energy usage and minimum GHG emission is totally dependent of the quality and diversity of the knowledge databases feeding the computer model. The ability to select the best processing method coupled with the best materials to use for the product is the key to success.

It is essential to make the right manufacturing decisions early in the design process, before the cost penalty of making changes becomes too high. The database for manufacturing selection would enable the best manufacturing method to be selected for a component, by linking the manufacturing method directly to the design. It would do this by matching the physical and shape characteristics of the component to the ability of a manufacturing

process to produce it. Variables like size, material precision, surface finish and batch size would be juggled to find the optimum compromise between performance (including environmental performance), productivity and cost. Examples of the broad process classes that would be included in the database are: fabrication, casting, moulding, deformation, powder methods, composite forming, machining, joining, rapid prototyping. Even now there are well over 120 processes within these classes.

Design engineers are faced with the problem of selecting the right material for a new product. Metal, ceramic, composite or polymer? A new material or an old one? What about weight, operating temperature, safety and cost? What about material production energy? With a materials selection database the best-fit solution could be found in seconds. Because the database would encompass all engineering materials, a set of attributes could be selected e.g. minimum weight for a particular stiffness, and the computer would do the rest. The database would contain the mechanical, thermal and electrical properties for existing ceramics, metals, polymers, natural materials and composites and it would have the facility to predict the properties of "new materials." Materials would be quickly located according to their class using an identification tree. Useful classifications would be:

- Ceramics
- Conductors
- Copper alloys
- Ferrous metals
- Foams
- Light alloys
- Metal matrix composites
- Non-ferrous materials
- Polymers
- Woods

Other databases could be added as required e.g. software to identify the best standard structural sections suitable for a particular load-bearing task. Materials that are used to carry loads in mechanical and civil structures are manufactured in a wide range of standard shapes among which the commonest are I-sections, tubes, box-sections and rectangular solid sections. Access to a section database would allow the engineer to choose optimal structural sections (open, closed and solid) - e.g. to minimise cost or weight or environmental impact for specified geometry and structural performance and to compare sections made in different materials.

Maintaining the technical data for the entire world's engineering materials and every known manufacturing process is no mean feat. It requires agreement on standardisation of definitions, particularly those in the environmental field such as energy content or recyclable fraction.

7. Scientific model development

Once all the parameters have been established for the above modules it becomes possible to start integrate all the modules into a single mathematical model. Modelling the total lifecycle using compatible software and hardware would allow smooth inter- and intra-module information flow. Currently, a wide variety of software and hardware is used for different applications, which results in impedance of interfacial information flow. The construction of an interactive numerical model for product/process/material design and optimisation is the objective of the lifecycle model.

8. Design Sensitivity Analysis

Once a model has been constructed it has to be fine-tuned to assess how changes in one parameter will affect the other variables. This is known as design sensitivity analysis (DSA). It is used to quantify the relative importance of various design/model parameters to the system response. DSA would be used to optimise the performance of each module within the lifecycle framework-a by embedding simulations in an optimisation program which iteratively updates the design until an optimum is found. When the modules are integrated into a single entity the overall model design has to optimised by considering the effect of changing the variables of one module on the other modules. Design sensitivity analysis on the complete system would enable a numerically-optimised model to be constructed.

9. Change process

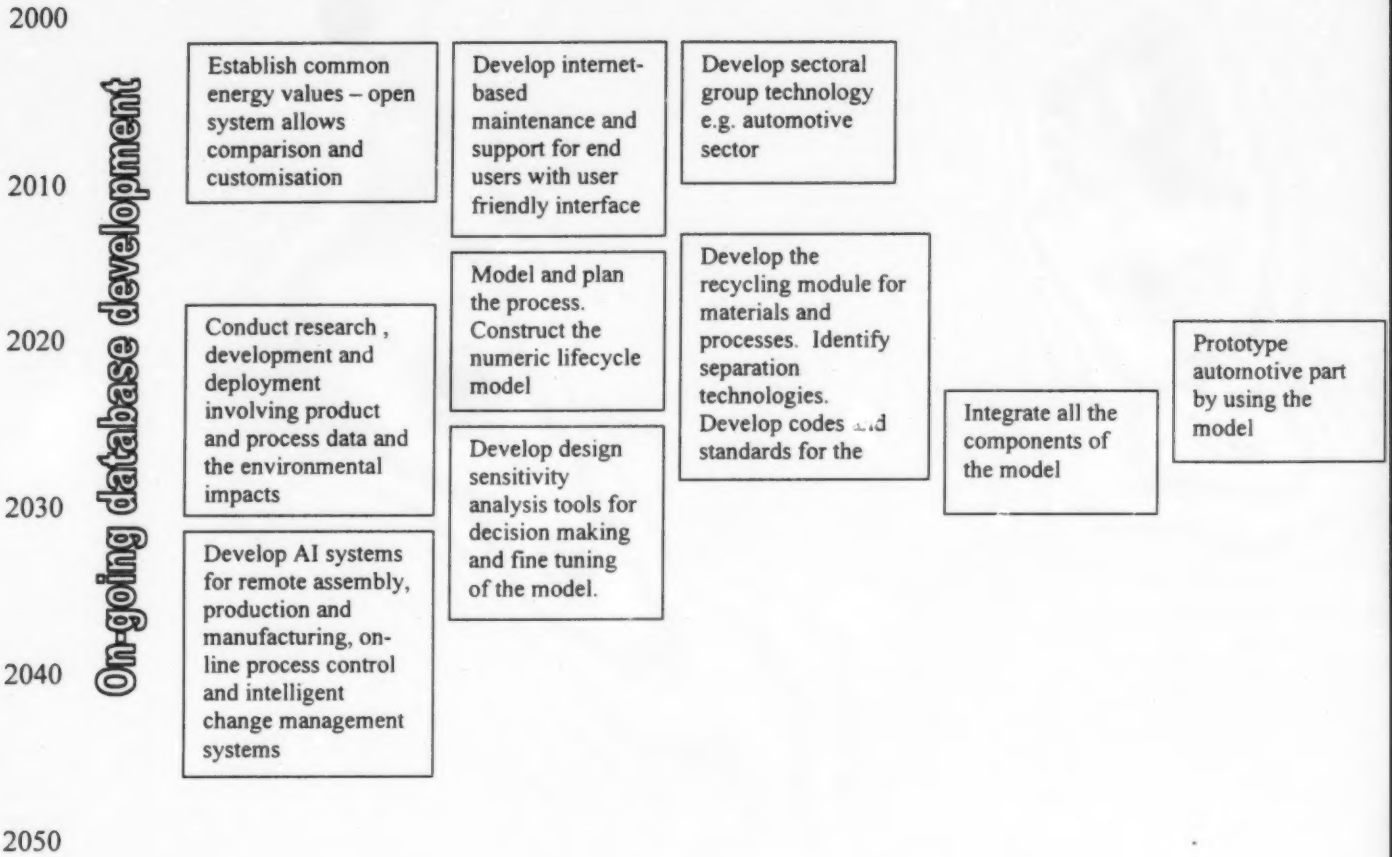
The use of the optimised model would identify shortcomings in technology that would lead to the development of R & D programs. Through analysis of different industry sectors it could be instrumental in determining codes and standards and effecting their implementation.

10. GHG Emission Lifecycle Analysis Model

The final model would easily identify major GHG sources in a process and would be able to optimise all the parameters to minimise emissions and energy usage. It would have a user-friendly interface. Maintenance and support would be provided to end users.

Model Development

Time Line


2000
2010
2020
2030
2040
2050
On-going database development
Establish common energy values – open system allows comparison and customisation
Develop internet-based maintenance and support for end users with user friendly interface
Develop sectoral group technology e.g. automotive sector
Model and plan the process. Construct the numeric lifecycle model
Develop the recycling module for materials and processes. Identify separation technologies. Develop codes and standards for the
Integrate all the components of the model
Prototype automotive part by using the model
Conduct research , development and deployment involving product and process data and the environmental impacts
Develop design sensitivity analysis tools for decision making and fine tuning of the model.
Develop AI systems for remote assembly, production and manufacturing, on-line process control and intelligent change management systems

Appendix A

Technology Trends in Green Manufacturing
presented in 1998 to
The Computer and Automated Systems Association
Society of Manufacturing Engineers
by Prof. Neil Duffie, University of Wisconsin-Madison

Key issues in green manufacturing
Green manufacturing, also referred to as clean manufacturing, environmentally conscious engineering, and industrial ecology, refers to designing and delivering products that minimise negative effects on the environment through their use, production or disposal. It is a holistic endeavour intended to result in less waste, cleaner products and processes, a better and safer working environment, improved relationships between companies and local communities, compliance with government regulations, and enhancement of profitability and competitiveness.

Green manufacturing (GM) is a long-term process driven by government regulations and social factors that are dynamically evolving. Despite this, GM must be taken into account in decision making with regard to manufacturing because of the potential for significant and possibly unexpected current and future consequences.

The importance of green manufacturing
Awareness of GM is becoming a necessity for manufacturing engineers and managers. It requires rethinking of manufacturing systems. This includes pursuing environmentally related goals and objectives, non-traditional manufacturing processes, new marketing strategies, and product design for a lifecycle that includes manufacturing, maintenance, and eventual disassembly and recycling.

There are a number of very real and current issues to GM. They includes the exponential increase in laws and regulations governing environmental issues and the associated reporting required, increased prosecution of companies for environmental violations, increased consumer demand for products made with GM practices, and increased scrutiny by investors, politicians, and environmental action groups.

New sets of international standards, such as ISO 14000, are being introduced that emphasise management systems that address environmental concerns, operations that consider energy and natural resource consumption, and systems for measuring, assessing and managing waste streams. New or modified manufacturing processes are being developed having ecological and economic benefits. These include reduction or elimination of cooling lubricants, use of watery dielectrics, laser surface treatments, and reduction in maintenance costs.

Where is GM heading?
GM is a relatively new concept about which there is significant confusion and misunderstanding about its components, costs, benefits and implementation. Its future trends are also uncertain. It is likely however, that customers will increasingly demand low-cost, quickly designed and produced, high-quality products characterised by extensive variety. They will also demand that processes that are environmentally responsible produce such products.

Whether GM is good business or a bad investment is being argued. On one hand, eliminating waste has potential for reducing cost and increasing value. On the other hand, investments can result in negative returns, decreasing dividends for shareholders. Middle managers are often focused on quality and productivity rather than environmental or marketing issues. This perspective can hinder development and implementation of GM.

To ensure success in GM, corporate cultures need to incorporate a vision of GM, a plan for its implementation and the consequences and costs of not achieving its GM goals. Along with the support of top management, a team approach with representation from engineering, production, purchasing and human resources has been found better than reliance on plant-level environmental experts or consultants.

Training of the team in the techniques of total quality management has been found beneficial. GM is likely to be an increasingly important issue because it is a crucial component in the international trend towards "sustainable development". Sustainable development has been a long-term goal to meet the needs of the current generation by developing systems and processes that do not compromise the needs of future generations. Achieving this will require interdisciplinary co-operation between politicians, economists, scientists and engineers.

Implementation of GM

Green manufacturing affects the entire manufacturing infrastructure including product design, product production, distribution, maintenance, and marketing.

The paper on trends in green manufacturing underlines the need to adopt a systems approach for development of an integrated process/product cycle. Total product life-cycle considerations have to be made right from the source of energy used to produce the material for the product to product disassembly and disposal.

Green Engineering Glossary

Cleaner Technology - A source reduction or recycle method that is applied to eliminate or significantly reduce the amount of hazardous substances, pollutants, or contaminants released to the environment.

Design for Environment (DfE) - Designing products to minimise waste during production, use, and disposal

Environmental Engineering - A branch of engineering concerned with managing the fate and transport of contaminants in the environment. Traditionally, environmental engineering had focused on "end-of-pipe" solutions to environmental pollutants.

Environmentally Conscious Design and Manufacturing (ECDM) - A view of manufacturing that includes the social and technological aspects of the design, synthesis, processing, and use of products in continuous or discrete manufacturing industries

Green Design - Treating environmental attributes as design objectives rather than as constraints. Green design incorporates environmental objectives while maintaining product performance, useful life, and functionality.

Green Engineering - The study of product or process design for environmental compatibility without compromising product quality or function.

Industrial Ecology - An approach to the design of industrial products and processes that evaluates these activities on the basis of product competitiveness and environmental interactions.

ISO 14000 Environmental Management Standards - A series of international environmental management standards developed by the International Standards Organisation (ISO) that encourages businesses to manage the impact of their products, processes, or services on the environment. These standards were released in 1996 and are gaining international popularity. The ISO 14000 standards were written to mirror the ISO 9000 standards for quality management. ISO 14001 is a standard within ISO 14000 that deals with Environmental Management Systems. Companies may apply for ISO 14001 certification or self-declare ISO 14001 compliance if they meet the criteria specified within the standard.

ISO 14000 Environmental Management Systems Standards - Components:

Environmental Management Systems
Environmental Auditing
Environmental Performance Evaluation
Environmental Labelling
Life Cycle Assessment
Environmental Aspects in Product Standards

Life Cycle - The stages of a product's or process's life from resource extraction through processing, manufacturing, use, and recycling or disposal.

Life Cycle Assessment (LCA) - LCA is defined by the Society for Environmental Toxicology and Chemistry (SETAC) as "a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. LCA addresses environmental impacts under study in the areas of ecological health, human health, and resource depletion. It does not address economic considerations or social effects. Additionally, like all other scientific models, LCA is a simplification of the physical system and cannot claim to provide an absolute and complete representation of every environmental interaction."

Life Cycle Engineering (LCE) - A practice that incorporates all relevant information about technology, economy, and environment in a single decision-supporting management tool, available during the design phase.

Life Cycle Impact Assessment (LCIA) - The process of analysing the environmental impacts of a product or process throughout its life cycle

Pollution - Any activity that degrades the quality of a natural resource so that its use by humans and other organisms is impaired.

Total Quality Environmental Management (TQEM) - An extension of the principles of quality management to include manufacturing practices and processes that affect environmental quality. There is a growing trend toward integrating industrial and environmental outcomes within a quality framework.

Sustainable Development - Defined by the U.N. as development that meets the needs of the present generation without compromising the needs of future generations.

Appendix B

PROCESS MODELING

Georges Salloum, IMI, NRC

INTRODUCTION

Three facets of product and process optimisation involve simulation of structural behaviour, material flow and solidification. Simulation technology is used to improve part and mould design and for the optimisation of die casting, injection moulding, blow moulding and thermoforming operations. Such net shape material processing techniques, moulding, forming and casting are vital to the mass production of single or integrated components for numerous industry sectors such as automotive, packaging, appliances, electronics, telecommunications, medical, leisure and sports. The success of these industries in responding to rapidly changing customer demands will depend, on the ability to develop and apply state of the art technology in collaboration with other partners. Instead of the traditional method, where product and manufacturing engineering follow in a sequential order, the emphasis is put on developing the product and its production process concurrently.

Due to market globalisation, the appearance of high performance materials, increased product complexity and geographical variation of raw material and labour costs, more pressure is put on the material processing industries and end product manufacturers for constant innovation and process optimisation. Their customers' demand for higher quality standards and lower costs often presents a considerable challenge beyond the reach of the individual companies. Despite the introduction of tools like computers, advanced processing machinery and programmable controllers, industry continues to be plagued with problems such as voids, surface defects, flashes, cracks, warped parts, material degradation, wrinkles, specks, parts out of dimensional specifications and late delivery.

There are approximately 75,000 injection and blow moulders, thermoformers and die casters and over 10,000 die and mould makers serving a variety of industries and original equipment manufacturers. The processing of metal alloys and polymeric materials is characterised by the complex interactions between the material (resins, metal alloys and composites), equipment configuration including old and die design, and processing conditions. These interactions ultimately determine the processability of the material, the economics of the process and the properties of the final product. It is therefore essential to develop a unified approach that incorporates simulation models for the material behaviour, processing operation and product performance.

CONCURRENT PRODUCT AND PROCESS DEVELOPMENT

Figure 1 shows how a concurrent manufacturing approach can be applied to the development of new products and processes. The first stage is to plan the process and define the specifications for the part, old and machinery that will be used during the development cycle or for production purpose. It is very important technically and economically to select the best material, various tool steels, stainless steels, ceramics, graphite, and non-ferrous alloys such as Al, Cu-Be and Ni, during the construction of the old. Also, soft tooling materials including Bu-Sn, epoxy, urethane, RTV rubber and kirksite compounds are commonly used to produce composite moulds for rapid prototyping.

More recently, nickel, cobalt and tungsten based super alloys are being used for making inserts, cores, runners and gates to sustain high melt temperature and abrasive fillers. High speed and laser machining, EDM, WEDM, vacuum assisted casting, rapid tooling and prototyping technologies such as SL, SLS, LOM, SGC, 3D processing, lost foam casting, thermal spraying, NVD and electrochemical deposition are available to speed up the development process.

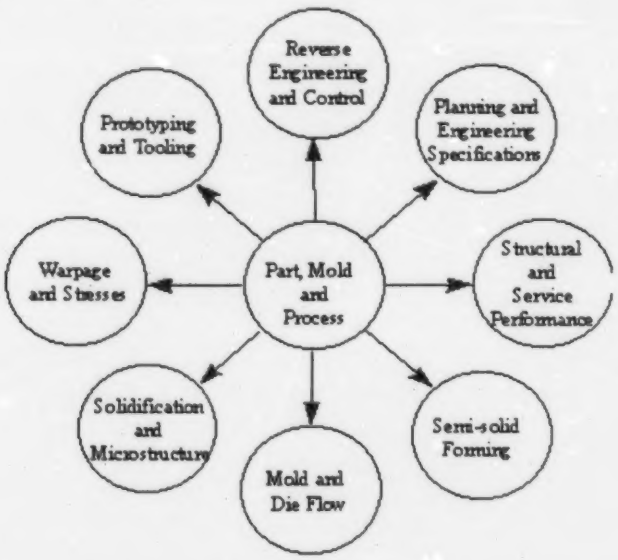


Figure 1: Integrated process/product development cycle.

The design of the old and the selected materials have a direct impact on the fabrication methods to be used. Two plate and three plate moulds with or without stripper or rotary plates, insert moulds, in-old decoration, stack moulds, parting line moulds, hot runner moulds, multicavity moulds, cam action and multi-slide moulds, lost core and collapsible core moulds, are few examples of the potential degrees of freedom available to the designers and mouldmakers. There are several types of processing machinery to be considered during the product-process development stage such as vertical and horizontal presses with or without rotary and shuttle tables.

Concerning the choice of the material for the product itself, there are a great number of polymers, metal alloys and composites to be evaluated. Commodity, engineering and high performance materials are available in specific or customised compositions for a given application or market. A material demand profile should be prepared taking into consideration the structural, functional, environmental, processing and recycling requirements. 3D CAD/CAM systems operating on workstations and personal computers are available to assist the designers and process engineers. They can access various commercial computerised databases provided by the material suppliers for the selection of the most suitable material.

The designer can apply computer simulation to conduct structural analysis, evaluate part functionality and verify that the part stands up to the demands that will be encountered under service conditions. Beyond this, experienced designers follow accepted practices, which directly influence the weight and strength of parts. They know it is important to avoid sharp corners and maintain relatively constant wall thickness to minimise stress concentrations.

As the part design evolves, it is also important to evaluate how various design options or alternatives influence the case with which the part can be manufactured. Some basic ground rules with respect to the number, location and size of gates and draft angles should be used to facilitate the filling and the ejection of the part from the old. However, to produce parts of high quality the product designer or the original equipment manufacturer must co-operate closely with the old maker and the material supplier. At the same time the quality of a part in terms of strength, appearance and dimensional tolerances is directly dependent on how it is produced. It is crucial to recognise that even a perfectly designed part can be ruined and fail specifications if it is formed under inappropriate conditions.

FINITE ELEMENT MODELING AND SIMULATION

Material processing generally involves the transformation from a solid state, usually in the shape of ingots, pellets or powder, unreinforced or reinforced, through a liquid phase into a final solid product with a specific shape, dimensions and properties. These phase transformations may involve several steps: heating and/or melting, forming, solidification and finishing. During processing operations the material experiences simultaneous fluid flow (laminar or turbulent) and transient heat transfer (conduction, convection and radiation). Flow regimes, depending on the nature of the material, the equipment, and the processing conditions, involve combinations of shear and extensional flows in conjunction with enclosed or free surface flows.

As shown in Figure 1, the optimisation of the process and the product must be based on a very good understanding of the interactions between the material behaviour during flow and solidification, and structural deformation. In general, computer simulations deal with two main aspects, i.e. mathematical modelling of the process, and numerical methods employed to find the solution. The analysis of material processing operations involves the solution of the equations of conservation of mass, momentum and energy. The equation of conservation of momentum represents the balance between the kinematics (velocity field) and dynamic variables (pressure and stress fields) acting on any given fluid. Therefore, it is necessary to introduce an expression that relates the velocity and stress fields. This relationship, called the "rheological constitutive equation", is used as the defining equation for specific types of material behaviour under flow, (i.e. Newtonian, viscoelastic, viscoplastic, etc).

The equation of conservation of energy represents the balance of heat transfer to and from the system due to convection, conduction, viscous dissipation, phase change, etc. Furthermore, in the case of compressible fluids, where density variations are important, it is necessary to employ an appropriate "equation of state" to describe pressure-volume-temperature (P-V-T) variations. Depending on a particular geometric configuration the deformation may be dominated by shear or tension, or may involve a combination of both. Shear-dominated flows are frequently associated with flows in closed channels or cavities having constant cross sections, whereas extensional flows often accompany deformations in certain types of free-surface flows.

The resulting system of non-linear partial differential equations representing the phenomena taking place during processing can only be solved using numerical techniques such as the finite element method. The use of numerical techniques has also gained popularity due to the development of solid CAD models capable of representing three-dimensional objects of complex geometry with automatic mesh generation based on topological searching and adaptive control algorithms.

The flow, solidification and structural models are inter-related since it is necessary to have information regarding the thermomechanical history in order to predict the microstructure and the final properties. This involves solving the conservation equations with fewer restrictions and therefore the complexity of the problem as well as the computational time will increase significantly. Finally, one can distinguish two dimensional (or membrane approximation) and three dimensional approaches that can provide the following capabilities:

a) information on moulding and casting characteristics, as well as the thermomechanical history (temperature, pressure, deformations and velocity profiles, etc.) experienced by the material during processing.

b) information on product quality and microstructure (distribution of density and crystallinity, part weight, wall thickness, wrinkles, residual stresses, shrinkage variation, porosity, orientation, permeability, dendrite arm-spacing, grain size, etc.).

c) information on processing parameters, dies and moulds such as runners, risers and gates, cooling channels and ejector pin layout, injection speed and pressure profiles, clamping and ejection forces, etc.

INJECTION MOLDING AND DIE CASTING PROCESSES

Injection moulding and die casting are the most important processes for the production of three-dimensional parts from plastics, metal alloys, elastomers and composites, and increasingly metal and ceramic powder. These processes involve the mixing, melting and/or heating of a material followed by its injection, under pressure, into a mould where it subsequently solidifies. The injection step involves the delivery of the melt from the tip of the cylinder or screw through the sprue, runners and gate into the cavity. During the filling stage, the material flows into the old under pressure or by gravity casting.

The filling stage is concerned with the transient non-isothermal flow (laminar or turbulent) of the fluid. When the cavity is filled, a high packing/intensification pressure is applied to force additional material into the old. The purpose of this step, is to introduce sufficient material into the cavity in order to compensate for shrinkage during the solidification stage and to ensure proper filling of complex parts. The increase of the material density in the cavity is responsible for the rapid increase of the pressure during this stage.

Simulation models are useful for the prediction of the filling pattern, short shots, voids and weld surfaces, pressure, velocity and temperature distributions, and the overall cycle time. Figures 2 and 3 show the predicted filling pattern during the injection moulding and die casting of two complex parts. In the solidification stage, a continuous decrease in cavity pressure is observed. Cooling is continued until the solidified material is rigid enough to be removed from the old without damage.

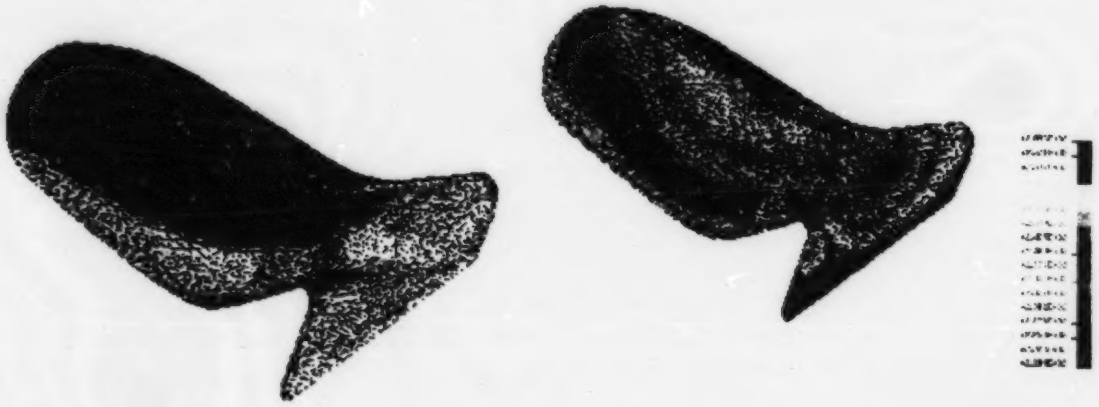


Figure 2: Injection moulding simulation of a car mirror holder.
a) Flow front at 60% of filling; b) Temperature distribution (°C).

These finite element simulations have also proven to be of great value in the design optimisation of part geometry, to determine the dimensions of old cavity and core and to control warpage and shrinkage while minimising process-induced residual stresses and deformations. The thermomechanical history experienced by the material during filling and solidification has a great influence on the structural behaviour of the part. These finite element methods are applicable to the following casting and moulding operations:

- Sequential injection moulding to relocate weld surfaces and to minimise warpage and residual stresses,
- Co-injection moulding for the production of multilayered parts offering functional characteristics in the inner or outer layers or to permit the use of recycled resins and cellular plastics.
- Gas-assisted, lost core and multi-shell injection moulding for the production of hollow cross sections in the moulded parts such as air intake manifolds, valve boxes and pump housings,
- High pressure and semi-solid die casting of Al and Mg components with thin wall or complex geometry,
- Low pressure, counter pressure and permanent old or gravity casting operations of thick wall parts which may require sand cores,
- Powder injection moulding of metal and ceramic composites and super alloys.

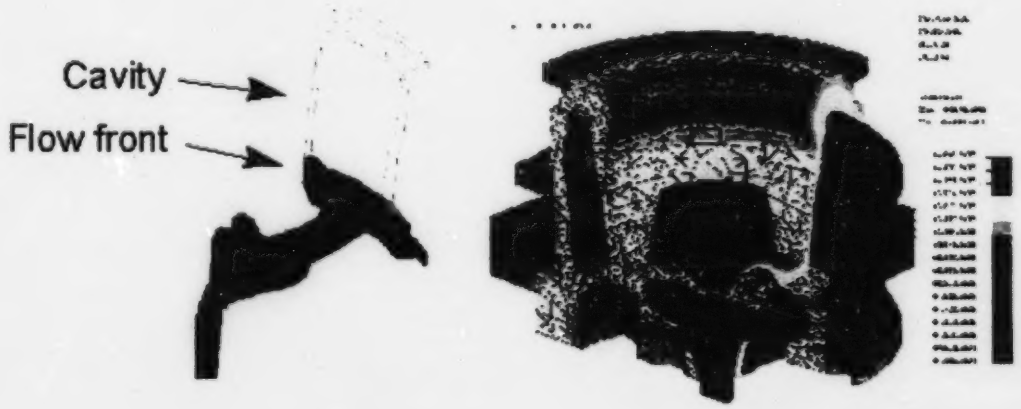


Figure 3: Low pressure casting simulation of a car wheel.
a) Flow front during 3D filling;
b) Temperature distribution in the old and part (°C).

BLOW MOLDING AND THERMOFORMING PROCESSES

Blow moulding is a commercially important polymer processing operation used in the manufacture of hollow plastic articles. Bottles, containers, automotive and appliances represent the most important markets for blow moulded plastic products. Blow moulding applications are expanding due to the success of multilayer extrusion processes. This growth runs parallel with the development of new high performance materials suited for the three basic variations of the process: extrusion blow moulding, injection blow moulding and stretch blow moulding.

In the extrusion blow moulding process, the raw material is fed to an extruder in granular or pellet form. The molten material is extruded through an annular die either continuously or intermittently in order to produce a hollow cylindrical tube called a parison. Once a parison of the desired length has been formed, the old is closed and the parison is inflated to fill the shape of the old cavity by internal air introduced through the die-head assembly. The part is then cooled, solidified and ejected from the old. Figure 4 shows the parison deformation and thickness distribution during the clamping and inflation stages.

In the modelling of this process, the first objective is the prediction of the wall thickness distribution of the moulded part and the stretch ratio of the inflated parison. It is now possible to relate the predicted wall thickness distribution to the programmable controller for setting the die gap during the extrusion of the parison, and for designing the old cavity and movable inserts or cores. The rheological complexity of predicting parison behaviour arises because this is a free-surface problem involving time dependent, non-isothermal elastic recovery from the flow of a viscoelastic fluid subject to gravity.

Injection blow moulding is a process in which a preform is injection moulded around a blowing mandrel. The moulded preform is later preheated or rotated instantly to a blowing station having a split old with the desired shape. The polymer is then inflated and solidified in much the same manner as in the extrusion blow moulding process. An important variation of either extrusion or injection blow moulding is the so-called stretch blow moulding process. In this process the parison or the preform are mechanically stretched before the inflation stage. The result is a lighter product biaxially oriented for better mechanical and optical properties.

Thermoforming is the process of shaping a heated thermoplastic or composite sheet by applying either positive air pressure, a vacuum, mechanical drawing, or combinations of these operations. The objective of computer simulation of thermoforming is the accurate determination of thickness distribution throughout the final part. This is of great importance in the fabrication of complex three-dimensional parts. In such a situation it is possible to have wrinkles, surface defects and holes at corners or unacceptable thinning in other highly stretched areas. The prediction of thickness distribution via computer enables the designer and process engineer to select an optimum from many possible alternatives.

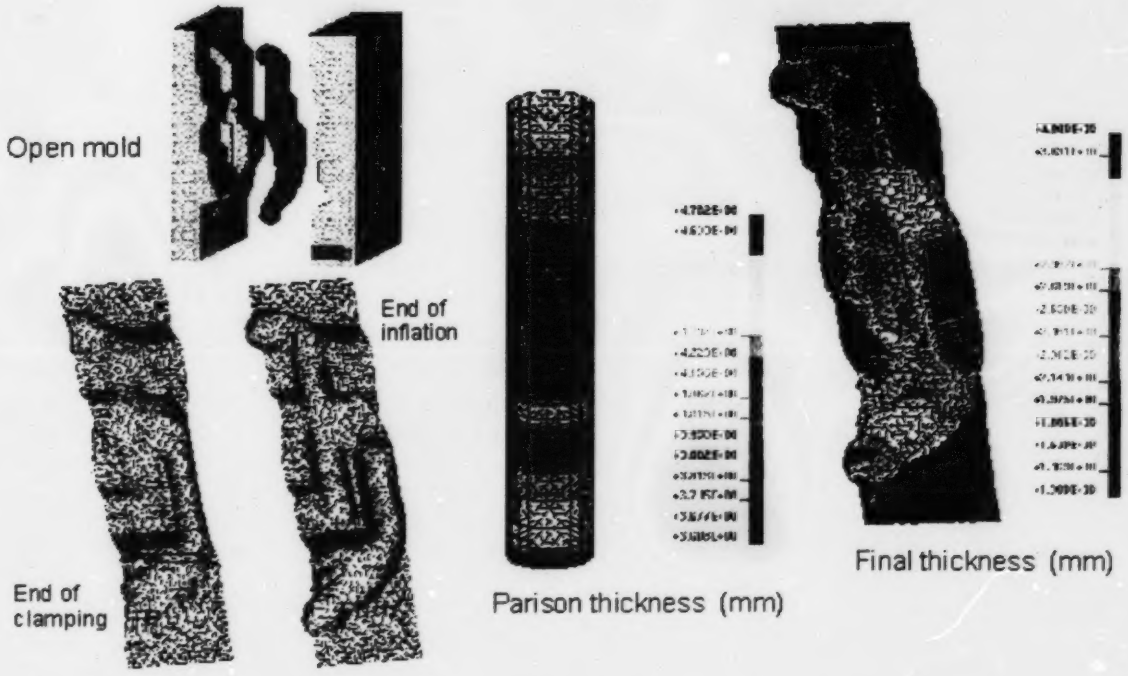


Figure 4: Extrusion blow moulding simulation of a car plenum.

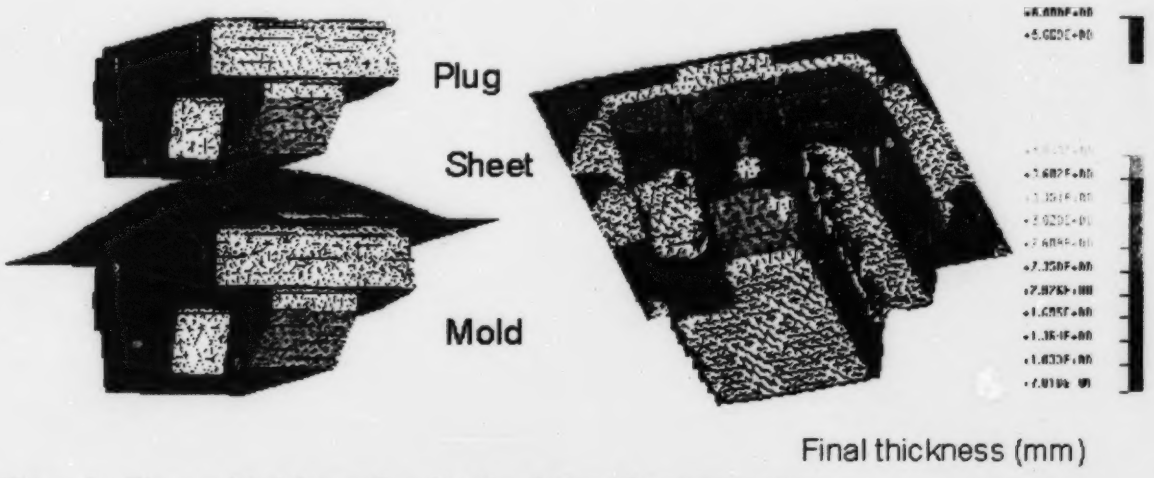


Figure 5: Plug-assisted thermoforming simulation of a scanner cover.

A finite element analysis based on the membrane approximation is applicable to thin-walled parts where the bending resistance can be negligible. In the case of thick walled parts, a three dimensional formulation is required or the membrane approximation has to be relaxed in order to take into consideration the presence of compressive and bending stresses. Figure 5 shows the predicted sheet deformation and thickness distribution for a scanner cover. The methodology is applicable to the following blow moulding and thermoforming operations:

- Extrusion and co-extrusion blow moulding for the production of containers and multilayered hollow products,
- Sequential extrusion and 3D blow moulding operations for the production of multifunctional and flashless parts primarily for the automotive and other transportation industries,

- Injection and injection stretch blow moulding with accurate dimensional control of bottles for the food, medical and industrial packaging industries,
- Vacuum and plug assisted forming with applications in food and medical packaging such as formed trays and blister packages,
- Pressure and twin sheet thermoforming with applications in panels and control cabinets, household and consumer products,
- Drape and matched old forming in automotive and industrial packaging.

CONCLUSIONS

Numerical simulation techniques which account for heat transfer, fluid flow, phase transformations and stress-deformation are generic and beneficial to processors, equipment and material suppliers and to end product manufacturers. The only practical means to achieve rapid tooling and the production of high quality parts is through the integration of part and old design with process development. Concurrent process modelling, design analysis and optimisation will improve product performance, prevent or control processing defects and shorten production time.

The interplay of part design, tool design, material properties, production conditions and part quality is extremely complex and involves a matrix of many variables. It is not reasonable to expect a team of engineers to deal with these complex interactions and optimise casting and moulding processes without the use of modern finite element methods.

In addition to modelling and simulation techniques, once the first prototypes have been produced, other performance tests should be conducted under service conditions. Among the tests most relevant to various applications, are the evaluation of chemical and impact resistance, clarity, substance absorption and degradation, permeability, microcracking, delamination, surface roughness, discoloration, etc.

Computerised process simulation can be used to monitor the influence of design alternatives on processability of the part and to select operating conditions that assure the required part quality. It is clear that finite element simulation increases process and product reliability.

Appendix C - The Factory of the Future

Factories of the Future

"The factory of the future will have two employees, a dog and a man. The man will be there to feed the dog; the dog will be there to keep the man from touching the machines."
Ottawa Citizen, Dec 1998.

There is immense diversity in product types from very small electronics-based products to large complex structures such as a nuclear submarine. However, the driving forces for changes in manufacturing these products are common:

- Ubiquitous availability and distribution of information
- Accelerating pace of change in technology
- Rapidly expanding technology access
- Environmental responsibility and resource limitations
- Increasing customer expectations

To meet these ever increasing demands will require:

- Next-Generation Manufacturing Processes and Equipment
- Rapid Product/Process Realisation
- Innovation Management
- Change Management
- Pervasive Modelling and Simulation
- Adaptive, Responsive Information Systems

It was felt that flexibility and agility would be the main characteristics of future manufacturing. Several key technologies were identified.

In the long-term, it was thought that fixtureless assembly would become a strategically important technology to decrease both energy consumption and unit production costs. For example, the assembly of numerous sheet metal parts in the automotive industry is currently performed using hardware fixtures prior to welding and/or riveting operations. Major energy, cost and lead-time savings could be achieved, if these fixtures were to be replaced by co-operating robots. In this case, two robots would be used to grasp two sheet metal parts and force the mating edges to form the necessary contact for the fastening operation. This new "fixtureless assembly" strategy substantially extends the range of applicability and performance of present day industrial robots in any manufacturing operation. It also leads to a far more flexible factory environment, in which product changes can quickly be made.

The logical extension of robotic assembly of individual parts is to develop technologies for automated assembly of large structures. The first step would be to develop the technology and machinery for an innovative and intelligent factory that is able operate remotely to manufacture, not only small systems such as cars, but larger structures such as buildings and ships also.

In the long-term multi-media design/multi-mode manufacturing will be the norm. The objectives will be to achieve high quality, reliability, flexibility and rapid delivery of products in a system where design, planning, validation and fabrication occur seamlessly in a monolithic workstation. This single workstation will encapsulate the activities currently performed by a set of distributed tools. Large reductions in floor space, cost and time cycle as well as increased quality, reliability and agility will be the signature of the new framework. Reconfiguration between small and large lot production will be effortless

and new manufacturing cells will embrace several different fabrication processes. The inherent industry dilemma of not knowing the product, the quality, or process that will be demanded down the road, will vanish. Transition across the spectra of product, process, and production volume will be trivial.

The Present: Current State of the Art in Product Realisation

Currently, design and manufacturing involves the integration of numerous hardware and software tools in an attempt to create a seamless product realisation environment. Many of the tools now in use were never designed to work together and their integration is difficult because of the number of interfaces. Interfacing results in inherent process-flow impedance.

The Future: Multi-Media-Design for Multi-Mode-Manufacturing

Multi-media computing has revolutionised the computer industry by supplanting a host of specialised systems with a single desktop environment capable of performing a wide variety of tasks. Multi-mode manufacturing would revolutionise manufacturing by replacing the numerous hardware and software tools, needed for current product realisation, with a single process planning and simulation station and a single fabrication station. This would reduce the process flow impedance associated with the interface between numerous specialised systems.

Multi-Mode-Product Realisation

The following nodes will define the new product realisation paradigm.

1. During product design, manufacturing process agents, supported by a rich multi-media environment, will guide the designer on process selection, process modelling and reliability conformance.
1. Manufacturing planning will then be carried out in single-station, virtual reality simulators that will verify deterministic manufacturing.
2. Multi-mode manufacturing will then be carried out on small footprint manufacturing stations that will combine all manufacturing process physics, robotics, inspection, and feedback information to the original designer. These multi-mode-manufacturing stations could be comprised of Stewart Platform-based hexapods.

   A hexapod is a dramatic departure from conventional machine tool design. This structure offers superior stiffness, low mass, and high acceleration relative to existing tools. It will be a highly reconfigurable (six degrees of freedom), modular, high-precision, high-dexterity machine. By virtue of these attributes, the hexapod would be an excellent choice as a single station fabrication cell for multi-mode manufacturing. Although the initial use for the hexapod was milling, its strength lies in its multi-processing capability. It can be used for such diverse processes as welding, plasma spraying, coordinate measuring and part manipulation. Fixtureless assembly could be enabled by a hexapod. Exploitation of this diversity in a single agile workstation would represent a major advance in efficiency.

Material Handling

New types of industrial robots will be developed capable of handling large, heavy parts or blocks with good working accuracy. Material handling is an increasingly critical issue as manufacturers seek greater the greater flexibility needed for a wider product range in variable batch sizes to meet today's diversifying demands. Current material handling systems, designed to handle one type of material with a predetermined configuration are not flexible or autonomous enough to meet the capabilities now being demanded-ability to automatically or autonomously respond to frequent changes in production technology and

environment, types of products and materials to be handled, and production schedules. Metamorphic material and product handling systems capable of meeting such demands need to be developed.

Intelligent Management Systems

Information management systems with decision-making capability to solve problems arising at any stage of assembly will be an integral part of the intelligent, remotely operated factory. They will use a comprehensive database containing knowledge accumulated from experience as well as all relevant information input, from the design stage to daily variables at the building site. Sub-systems will be developed to provide timely information on potential hazards at a site and other factors that might interfere with productivity, and to identify counter measures.

On-Line Process Control

Advanced control systems are used by industry to increase productivity, improve efficiency, and reduce waste. The implementation of advanced control leads to enhanced reliability and safety, reduced variations in product quality, and expanded flexibility in manufacturing to competitively meet change.

The focus of process-control research is to develop industrially relevant methods and tools. Current research areas include plant-wide distributed control, model-based predictive control, nonlinear control by neural networks and fuzzy logic control, and on-line process monitoring through advanced state and parameter estimation.

Practical control systems rely heavily on sensors and actuators to gather information in real time so changes can be detected and corrected if necessary. Dr. Jean Bussière, IMI, NRCC made a presentation to the group on sensors and control that is attached as Appendix E. The group emphasised controls and sensors as being important in the quest to optimise quality (GHG emission mitigation and energy consumption in this case) in manufacturing processes.

Miniaturisation

The paragraphs above address the assembly of relatively large components and structures. However, a significant future trend is miniaturisation. Technologies such as MEMS (MicroElectroMechanical Systems or simply micromachines) will be increasingly important. MEMS are touted to be the next step in the silicon revolution. The incorporation of new types of functionality onto a silicon chip that will permit it to think, sense, act and communicate will be enabled by MEMS. MEMS exploit the existing microelectronics infrastructure to create complex machines with micron-size features. These integrated microelectronic/micromechanical systems on a chip have many functions, including sensing, communication and actuation. Integration of microelectronic/micromechanical systems enables the creation of intelligent microsystems, which know where they are, what's going on around them, and can react to their environment. MEMS accelerometers, used as airbag-deployment sensors, are already widely used in the automotive industry, other uses in the automotive sector include anti-tamper, anti-skid, and active-vibration-control systems. More and more MEMS, such as commercial pressure sensors, microlocks for critical assemblies like nuclear weapons, and telecommunications applications such as micromotors that precisely position small mirrors and align fibre optics, are being demonstrated. In fact the world's smallest steam engine is a MEMS. Some future applications include free-ranging microrobots that could cruise through the bloodstream, report on conditions, and make repairs on a cellular level, as well as microfactories that could create entire tool chests of micromachines.

One thing is certain, the smaller, more complex machines of the future cannot be built with current methods: they must almost build themselves. The integration of biotechnology and genetic engineering with conventional mechanical and semi-conductor devices may well bring this about. Nanotechnology, design of materials, processes and products from the atom up will become increasingly important in meeting future demands where critical control of properties is essential.

Appendix D

HYDROGEN AS A CLEAN ENERGY CURRENCY

Prof. Ron Venter, University of Toronto

Can we predict the future?
Can we plan for the future?

The drivers for change have to be clearly defined. Will they be concerns about the environment or sustainable systems or the options for renewable energy? Both fossil fuel depletion and the need to mitigate the risk of climate change disruption caused by green house gases are often seen as the two fundamental drivers that will demand the introduction of hydrogen systems. Hydrogen can be produced from any energy source and will inevitably be produced from sustainable sources – it is never an energy source itself, rather an energy currency. A currency can allow energy transactions, it can be stored or moved, thus energy currency is a better descriptor for hydrogen than energy carrier. Hydrogen can be used as a fuel for residential, industrial and transportation use. It is clean–a zero GHG emitter–the only by-product of its combustion being water.

In planning for the future, manufacturing industries will be constrained to consider the upstream and downstream energy sources and their cleanliness. Planning for the future should include the widespread use of hydrogen produced from renewable sources. On a large-scale basis one of the options for producing hydrogen is using nuclear energy.

The hydrogen infrastructure drivers must be considered. Should hydrogen be produced from stationary local sources or should it be transported? Types of hydrogen storage systems have to be considered. Should reformers or water electrolysis be considered?

If we knew what the future hold with a 90% certainty we would probably invest in fuel cells and electrolysis. We need to plan new research and development strategies and stay the course.

At a recent conference on manufacturing efficiencies and the future, costs and personnel requirements dominated. Environmental concerns were an issue, but energy systems were excluded.

Appendix E

Sensors for Intelligent Processing of Common Materials
J. F. Bussière
National Research Council Canada
Industrial Materials Institute
Boucherville, Québec

INTRODUCTION

Intelligence, according to a commonly used dictionary, is "the ability to learn or understand or to deal with new or trying situations"[1]. It is easy to argue that sensors are essential for any system to react intelligently to such situations. In fact, the absence of sensors would in most cases cause the failure to recognize the occurrence of such situations. This also applies to materials processing systems where sensors provide information, which is interpreted in terms of imbedded models and algorithms, which provide the rationale for dealing with the encountered situations.

Most materials processing systems in industrial use today are automated on the basis of keeping process parameters within a certain narrow range based on prior experience and simple models and are not generally referred to as "intelligent" since they are not generally able to react to "new and trying" or unprogrammed situations such as variations of incoming materials properties, variations of equipment or unstable conditions such as during setup or grade changes. The concepts of intelligent processing systems designed to deal with such situations emerged in the early eighties with the goal to more effectively produce advanced military and aerospace materials whose performance is sensitive to microstructure and are therefore more difficult to produce. Through the eighties and early nineties the focus has continued to be the production of advanced or high performance materials such as forging/forming of aerospace alloys, high performance composites, the production of high performance alloy powders for aircraft engines, ceramic matrix composites, etc.

Although intelligent processing can lead to considerable benefits when applied to advanced materials, these materials correspond to a small fraction of the economy of even the most industrialized nations such as the U.S. As illustrated in fig 1 and recently pointed out by Sohn in an article on the future of the metallurgical industry [2], even a large "sunrise" industrial sector such as the fabrication of electronic components is still much smaller than many traditional industries and has only recently been surpassed for instance by the combined "stone, clay and glass industries" in terms of the value of manufacturers' shipments in the U.S. The combined 1995 shipments of such steel related smokestack industries as "Blast furnace and basic steel products" and "Iron and steel foundries" is approximately 90 B$, i.e. roughly equal to the total of "Electronic components" [3]. Another sector, such as "Chemical and Allied products" which had annual shipments of 368 B$ in 1995 represents approximately 10% of all U.S. manufacturing and employs over 1 million people in the U.S. alone.

Considering the shear size of these industries and their need for competitive survival it appears that there are tremendous opportunities for the development and application of new technologies such as sensors and intelligent processing to improve productivity. In this paper I show that some of these concepts are already taking hold in industries producing the materials that we deal with on a daily basis.

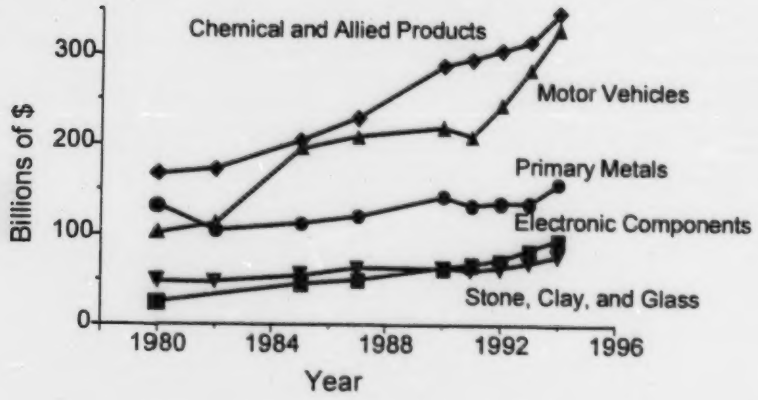


Figure 1: Annual values of U.S. shipments (in billions of $) by selected industries (adapted from ref 2 using data from ref 3).

First I will briefly review the basic concept of Intelligent processing including new types of sensors sensitive to materials behavior and microstructure to provide real time feedback during production. I will then briefly describe some common goals expressed by industries producing common materials and identify desirable sensor attributes and priorities. I will then present examples of recent sensor developments which correspond to these priorities and which have been tested in plant conditions.

INTELLIGENT PROCESSING

The concepts of smart or intelligent processing emerged in the early eighties from the US Air Force and were elegantly and concisely described in a visionary paper by N.M. Tallan [4] published in 1982. Programs were then initiated in the mid eighties by the Defense Advanced Projects Agency (DARPA) to produce the advanced materials required for emerging defense systems in a more cost effective manner and also to address concerns about competitiveness of U.S. industry [5,6].

Tallan [4] distinguishes the essential features of a programmable automated process from those of a smart adaptive process as illustrated in figure 2. Whether a process is simply automated or smart, basic features are required such as a basic model of the process, a data base, a set of process requirements, a process controller and some means of sensing and feeding back process parameters (such as temperatures, pressures, flow rates, etc.) so that adequate control can be maintained (see figure 2). The model can be based on experience acquired heuristically by varying the parameters and relating them to product quality; it can also be based on a scientific analysis of the process or a combination of both approaches. In a simple automated process, once a process plan is produced the role of the controller is to carry out predetermined steps repeatedly and reproducibly. Such processes provide important improvements compared to operator dependent control but can also reproduce bad parts automatically just as easily as good ones. It is therefore essential as pointed out by Tallan [4] that such processes incorporate traditional inspection to make certain that production corresponds to requirements and that there is

no variation in time due to changes in the equipment, in the incoming raw materials or in process variables that were not included in the initial process plan.

However, addition of new sensors to monitor material properties and geometric parameters (as shown in italics in figure 2) provides the possibility to assess conformity to initial plan at all times during the process thus providing data for improvement of the model and the data base. In addition, adaptive learning and artificial intelligence (also shown in italics) could be used to determine complex relationships between process parameters and final product characteristics. This information could then be used to improve manufacturing models and to generate a more effective plan for the next increment of the process. As pointed out by Tallan, this would lead to a paradigm shift for inspection from being predominantly a tool for in-process product assessment to a combination of continuous in-process product and process assessment.

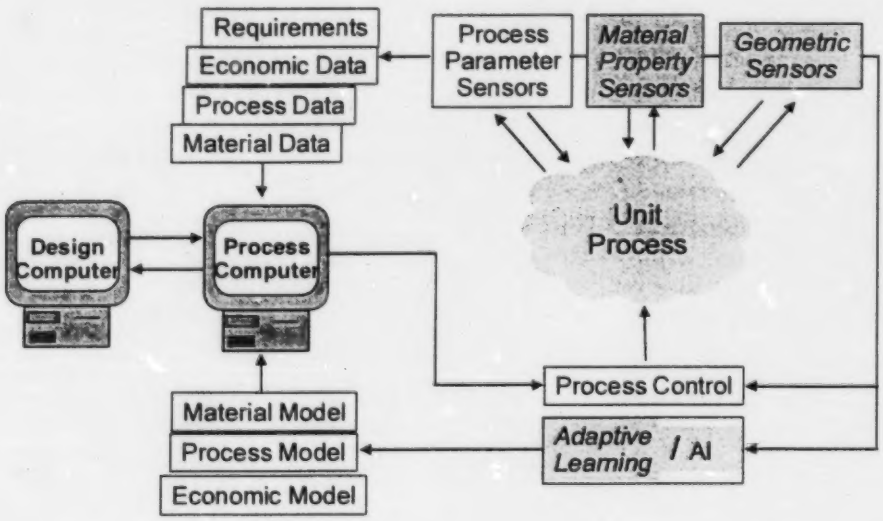


Figure 2: Smart, adaptive, automated process incorporating material property and geometric sensors as well as adaptive learning capabilities as shown in italics in the shaded boxes (adapted from ref 4).

Since Tallan's visionary article of nearly twenty years ago, computer power has continued to grow exponentially, making sophisticated process models more readily available. Optical vision and image analysis systems have also proliferated, making it possible to determine geometric features of products in real time and material property sensors have gained considerable interest both from research and industrial points of view. The concepts of Intelligent processing have also been refined and applied to a number of processes [5,6].

INDUSTRY VISION AND SENSOR NEEDS

As pointed out in the introduction, process industries such as primary metals and chemicals represent a large fraction of manufacturing and their ability to compete in the global market is of prime economic importance. Because of their size and the nature of their activities these industries also produce most of the hazardous and nonhazardous waste and consume most of the energy associated with manufacturing and are under considerable pressure from governments to improve environmental performance. In the U.S., process industries such as steel, aluminum, metal casting, chemicals and petroleum refining consume 81% of the total energy of the manufacturing sector and generate over 80% of waste and air emissions. The future of these industries will therefore depend to a large extent on their ability not only to meet increasing customer demands, but also to meet environmental pressures. Faced with these pressures these industries have established a partnership with the U.S. Department of Energy (DOE) and have produced vision documents [7] as to where they want to be in the year 2020. Several of these industries have also produced Technology Roadmaps, which indicate the technological barriers and research priorities to achieve this vision[8].

From these documents it is possible to extract a shared vision for the year 2020 across the different industries:

- Production will be more energy efficient and environmentally friendly
- Manufacturing will exhibit greater agility to rapidly meet changes in customer demands
- The availability of process models, real-time measurement tools and process controls will further improve productivity, quality and product properties

We list here a few examples of specific sensors and control needs for a number of industries:

a) Steel making:
   - Robust sensors to measure chemistry and temperature during steelmaking
   - Rapid, inexpensive slag composition analyzer
   - Instant steel bath and off-gas analysis of Basic Oxygen furnace

b) Steel Rolling and finishing:
   - Methods for effective communication between end properties, production route, microstructure and cost

c) Aluminum Industry:
   - Models, sensors and controls for primary production, casting, semifabrication (rolling, extruding, etc.) and finished products

d) Specific sensors for the aluminum industry:
   - Low-cost inclusion sensor
   - Non-contact sensor for in-line measurement of temperature and performance properties

e) Glass industry sensors and control needs:
   - Contact and non-contact temperature sensors
   - Refractory temperature and thickness sensors

- Sensors that detect and assess physical properties of glass such as viscosity during manufacturing

Although these examples are only a sampling of industrial needs they indicate certain trends towards increased use of intelligence based on models and sensors. Many of the sensors relate to material properties or performance. From these vison and technology roadmap documents [8] and experience that our laboratory has had with industry over the years, I have established a list of sensor types for Intelligent processing. These are listed below (Table 1) in rough order of priority:

Table 1: High Priority Sensor Measurements for Intelligent Processing

- Chemistry - Temperature - Microstructure and material behavior and/or response - Material Properties and/or Performance (e.g. mechanical properties)

It should be noted here that, except for temperature, the quantities to be measured relate to the material itself, a characteristic of the new type of sensors required for the Intelligent processing of materials. Some readers may be surprised to see temperature near the top of the list since temperature sensors such as thermocouples and pyrometers are readily available. However, what is required is the temperature of the material itself, including internal temperature, in sometimes very harsh environments, in real-time during processing. This type of temperature measurement may therefore also be considered to be part of the class of sensors included in "materials response".

In addition to measuring these properties, sensors also need to meet a number of attributes in order to be used by industry: 1) They must have sufficient accuracy, 2) They should preferably be noninvasive to minimize installation costs and modifications to existing processes, 3) They should be robust and reliable and 4) Cost effective, i.e. return on capital investment should be very short term.

In the remaining part of this paper I will give examples of sensors which are being developed to make the processing of common materials more intelligent. In most cases these sensors are at an early state of development and have not been integrated in sophisticated processing systems such as depicted in figure 2. However, the examples have been chosen to both illustrate sensors of the different categories listed in table 1 which have been used in harsh industrial environments and to demonstrate in many cases the economic benefits that will result from using such sensors. Most of the examples will be taken from the steel industry although in some cases the same sensors could be used directly on other materials. One last example will concern thermal spraying of coatings where characterizing the particles being sprayed (i.e. response of the particles to torch parameters) is shown to provide a better control of coating microstructure.

RECENT SENSOR DEVELOPMENTS

Chemical analysis:

As mentioned above, chemical composition is one of the most important parameters which affects final properties of a material and therefore needs to be accurately controlled. In the case of steel production, composition measurements are required at several stages of the process. One such process that accounts for roughly 60% of steelmaking is basic oxygen steelmaking in a Basic oxygen furnace (BOF) which is typically charged with 200 tons of pig iron from the blast furnace and 90 tons of scrap. This results in liquid iron containing typically 4.5%C, 0.5%Si, 0.5% Mn and 0.06%P and a number of impurities. The purpose of the BOF is to reduce carbon content to less than 1% (and usually less than 0.1%), to control the levels of sulfur and phosphorous and to raise the temperature of the liquid steel to approximately 1650°C. To reduce the concentration of these elements, pure oxygen is blown into the furnace for about 20 minutes through a water-cooled lance causing vigorous agitation and an oxidation process whereby these elements, along with some of the iron, get oxidized during the blow to form gases such as CO and CO2 and slag. The reaction generates the necessary heat to run the process.

Process control of oxygen steelmaking is very important as it directly affects heat production times. Accurate control results in fewer reblows and steel bath cooling, which are time consuming and expensive. Improved control also results in better iron yield, greater productivity, better refractory lining life and overall lower cost of production. Process control strategies rely mostly on "static" models that are based on process parameters with no feedback from materials behavior sensors (see for instance ref 9). However, a simple and effective sensor for estimating carbon content of low carbon heats (0.06% or less) was recently developed at Bethlehem Steel, which offers the possibility of dynamic response [10]. The sensor is simply a ruggedized photosensitive cell placed approximately 10m from the mouth of the BOF and which monitors the light emitted by the BOF due to combustion of CO at the mouth of the vessel as shown schematically in figure 3. It belongs to a class of sensors which provides an indirect measurement since there is no general direct relationship between light intensity and carbon content. Light intensity vs. accumulated oxygen blown is plotted as shown in figure 4 and features of the curve correlated with carbon content. It was in particular determined that the extent to which the light intensity decreases after reaching its peak value is strongly correlated to the carbon content in the metal. By making measurements on a number of heats an empirical correlation is obtained. For carbon levels less than or equal to 0.05% the standard deviation error in carbon estimation using this technique is in the range of 0.005% to 0.007% compared to 0.01 to 0.02% without the sensor. The carbon estimates are used to either extend oxygen blow or to shorten it resulting in reducing the frequency of oxygen reblows which waste time and oxygen overblows which can damage the refractory lining. The system not only provides better carbon control but also helps the steelmaking operators to sometimes "quick tap" heats (i.e., tap heats without taking

chemical analyses) to boost productivity. Other sensors based on optical analysis of the gases exiting from BOF furnaces are being developed and hold promise for the future [11].

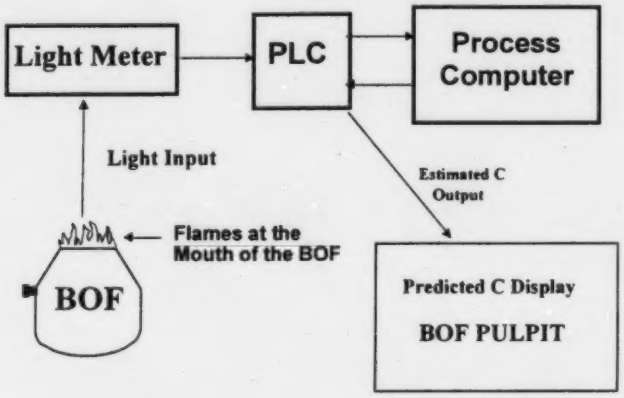


Figure 3: Schematic of lightmeter sensor for determining carbon content during steelmaking in a basic oxygen furnace (BOF) developed be Bethlehem Steel (from ref 10, reprinted with permission)

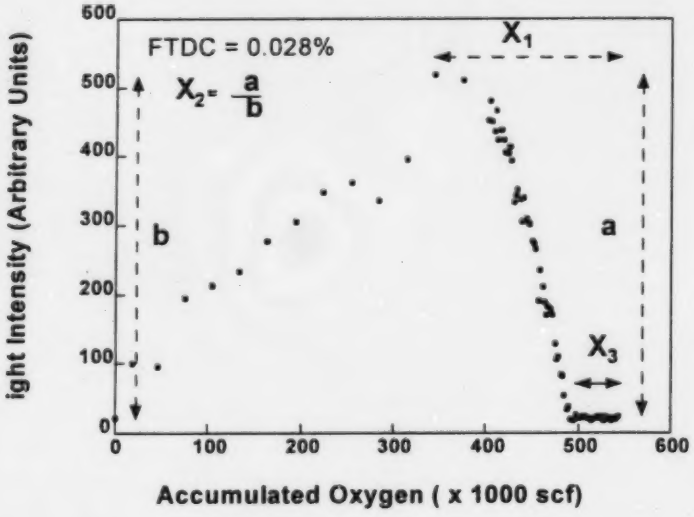


Figure 4: Observed light intensity by the lightmeter of figure 3 during oxygen blowing in a BOF. Features such as light intensity at the beginning of blowing, b, the amount of oxygen blown at peak light intensity, a, and the amount blown in the flat part of the curve at the end, X3, are used to predict final carbon content (from ref 10, reproduced with permission)

Another, more direct, technique for measuring chemical composition remotely, and which has potential for applications in many industrial processes, is Laser Induced Plasma Spectroscopy (LIPS). In this technique, a high power laser pulse is focused on the material to be analyzed resulting in ablation of a small quantity of material and ionization to form a high temperature plasma (20000K-30000K). The setup is shown schematically in fig.5. The light emitted by the spark or plasma is analyzed with a spectrometer with a high time resolution. The light emitted in the first few hundred nanoseconds is very broadband and corresponds to brehmstrahlung. As the plasma cools down, however, distinct atomic emission lines are obtained with excellent signal to noise ratio. Measurements are therefore obtained by gating the detector so as to detect light for a period of typically microseconds after an initial delay of a few microseconds. Relative detection limits of between10 and 100ppm can be achieved for most detectable elements in various matrices (e.g. Steel, rubber, rock, glass) [12].

LIPS offers a number of advantages for in process measurements of chemical composition. In addition to being remote and noncontact, and usable in an ambient gas atmosphere of normal pressure the analysis is rapid, typically of the order of one second or less; it can be used for electrically conductive or insulating materials in both the solid or liquid state. In addition LIPS analysis does not require sample preparation whereas the spark discharge technique, another atomic emission analysis method, is easily affected by the surface condition and grain structure and its range of use is limited.

LIPS has been developed in recent years for measuring the composition of liquid steel and is being tested for analysis of liquid stainless steels in the ladle prior to continuous casting [13,14]. The probe, shown schematically in figure 6, is in the early commercialization phase with Bailey Engineers. The probe which contains the laser and spectrometer is approximately 2m in length and 35 cm in diameter and operates by introducing the refractory-lined penetration tube (~ 8 cm dia) into the molten metal. The level of liquid metal is measured with a rangefinder. An umbilical cord is used to transport cooling water, gas, power and data signals to and from the sensor head.

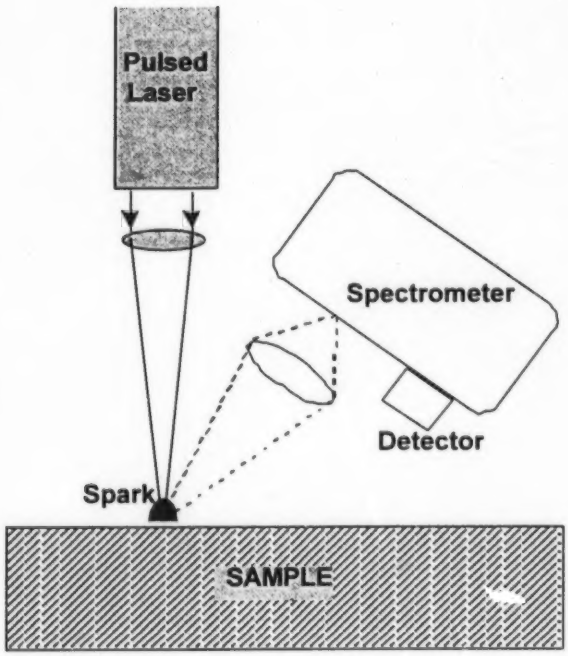


Figure 5: Schematic of laser induced Plasma spectroscopy. An intense laser pulse produces a plasma or spark. Elemental composition is obtained from atomic emission lines of the elements in the sample.

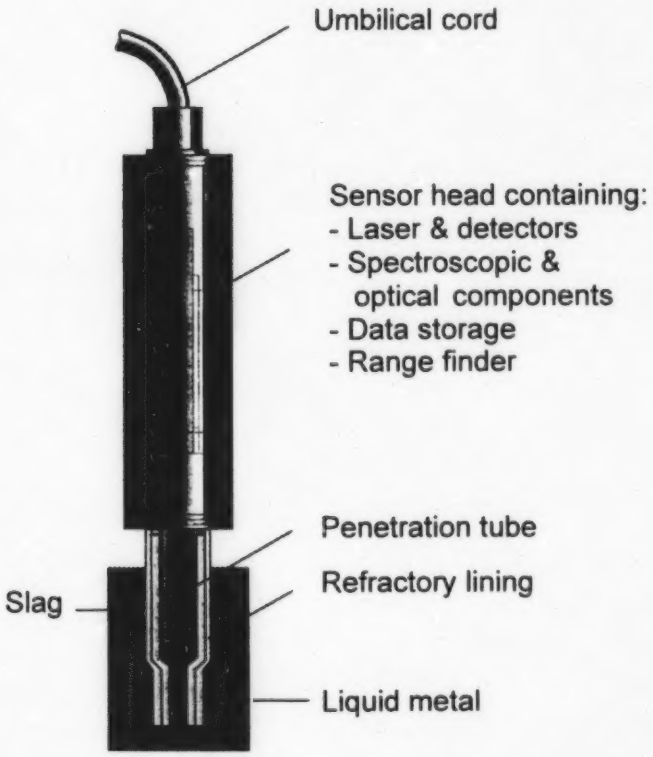


Figure 6: Laser induced plasma spectroscopic probe developed at Lehigh University and commercialized by Bailey Engineers Inc. The sensor has been tested for analysis of elements in full size ladles of steel. Reproduced with the permission of Dr Y.W. Kim.

Using this laser-plasma probe, analysis of more than 10 elements is possible in 30 to 60 seconds in comparison to a range of 6 to 60 minutes for present state-of-the-art analysis which requires extracting molten steel from the ladle, casting and cooling a sample, sending it to the laboratory and obtaining the result. Although 6 minutes may seem like a short time one should take into consideration that processing one heat takes on average 30 to 45 minutes. Reducing analysis time by five minutes results in an immediate increase of productivity of 10 to 15%.

Temperature:

As mentioned earlier, once the chemical composition is known the second parameter in terms of importance is temperature of the material being processed, which is often different from the temperature of the surrounding environment. An example of the need for accurate temperature is in the continuous processing of sheet metal such as continuous annealing of aluminum and galvannealing of steel. Continuous annealing of cold rolled aluminum is done at approximately 360 °C. In this process it is important to insure that the material is completely recrystallized. This depends on the time spent at the set temperature. Noncontact measurements of temperature can be obtained with

infrared pyrometers. However, because of important variations of emissivity, it is difficult to measure the temperature of the sheet even when two color pyrometers are used and temperature errors of the order of 50°C can result. Because of this, operators tend to be conservative and slow down the line to insure that complete recrystallization has occurred. An improved system was developed in our laboratory a few years ago [16]. It is based on coupling a two-color pyrometer via fiber optics to a conical or double wedge gold coated reflector placed above the sheet as shown schematically in figure 7. The reflector together with the sheet makes the measurement conditions closer to a black body and less sensitive to emissivity. Two advantages of the reflector geometry are the possibility of a large standoff distance between sheet and reflector (~ 7 cm) and insensitivity to substantial variations in this distance (±3 cm). As a result of the increased accuracy of the sensor, ~ 2°C, the speed of the aluminum continuous annealing line was increased by 25%, a very substantial increase in productivity.

Another approach for measuring the temperature of a metal sheet on-line has recently been developed at Oak Ridge National Laboratory as part of the Advanced Process Control Program of the American Iron and Steel Institute (AISI). The application in this case is galvannealing of sheet steel, a process that involves passing a steel sheet through a zinc bath as in conventional galvanizing and then through a galvannealing furnace at elevated temperature. The high-temperature causes interactions between the iron and the zinc producing a number of zinc-iron phases that need to be formed in certain proportions to result in superior properties for automotive applications.

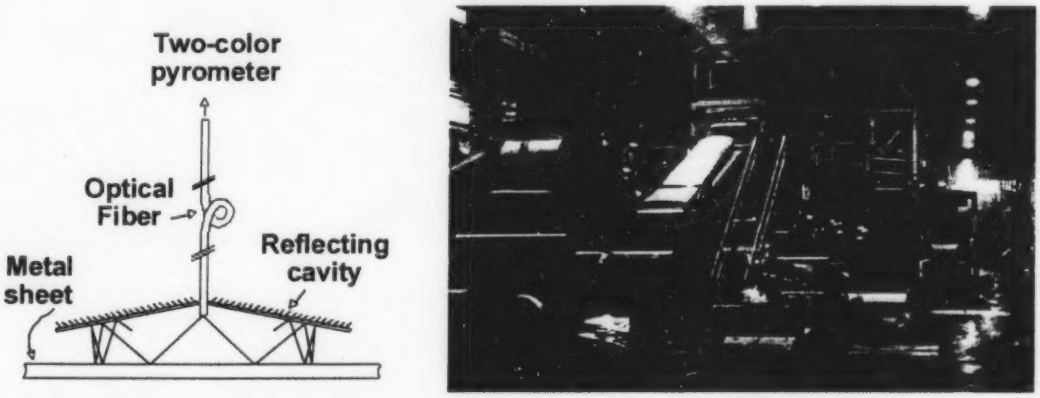


Figure 7: Noncontact temperature sensor based on a two-color pyrometer coupled to a reflecting cavity placed over a metal sheet (left). The system has been operated for several years in an aluminum continuous annealing line (right).

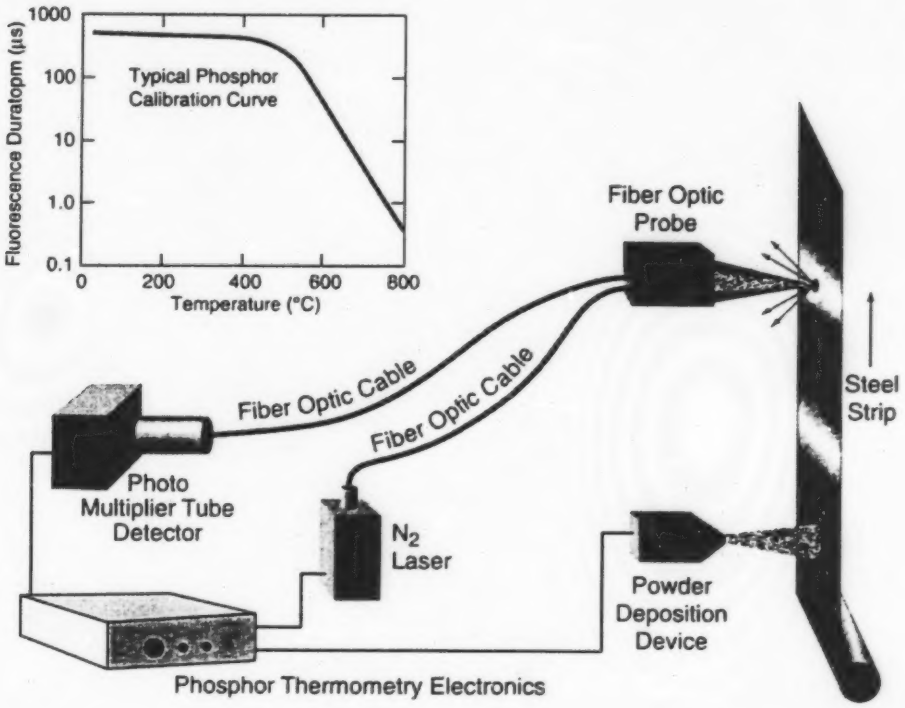


Figure 8: Schematic of phosphor thermometry system developed at Oak Ridge National Laboratory for the non-contact measurement of temperature during the galvannealing of steel. A phosphor is deposited on the steel sheet; it is then excited with a laser and the resultant fluorescent light detected. The decay time constant of the fluorescent light is then converted into temperature (see inset). The system has been successfully tested on line at National Steel.

A key parameter in the processing is temperature of the sheet in the galvannealing furnace. Unfortunately, as in the case of continuous annealing above, temperature measurement is made very difficult with infrared because of the very large change in emissivity as the coating changes from a nearly perfect reflector (low emissivity) when the zinc is liquid to a much higher emissivity in the solid state. The technique developed at ORNL is independent of emissivity and is based on phosphor thermography [17, 18]. In this technique, shown schematically in figure 8, phosphor material, typically a ceramic, is sprayed on the coating and then excited with a laser beam. The laser light is absorbed by the phosphor and re-emitted as fluorescent light, which decays with a time constant that strongly depends on temperature (see inset of figure 8). The fluorescent light is then detected, the lifetime measured and converted to temperature. Accuracy of the measurement depends on the steel temperature range and is typically in the range of 1 to 5°C. The use of this sensor should lead to the more consistent production of coatings with good corrosion resistance, a very desirable property especially when that sheet of steel ends up in your car. Commercialization is underway at Bailey Engineers and installations are planned for the near future.

MATERIALS PROPERTIES AND PERFORMANCE:

Customer specifications generally relate to materials performance or materials properties such as, for instance, wear resistance, formability or mechanical properties such as yield and tensile strength. This is the case, for instance for cold rolled and annealed steel sheets for the automotive and other markets. For such applications it would be desirable to have a sensor which monitors yield strength and formability directly on the production line. Measurements are presently made by cutting out samples at each end of a coil. This is time consuming, can cause delays in shipping and also provides no information of the thousand or more meters between the ends. Online measurements could also be used as a tool for process control. There have been a number of efforts over the years to nondestructively measure mechanical properties on the production line

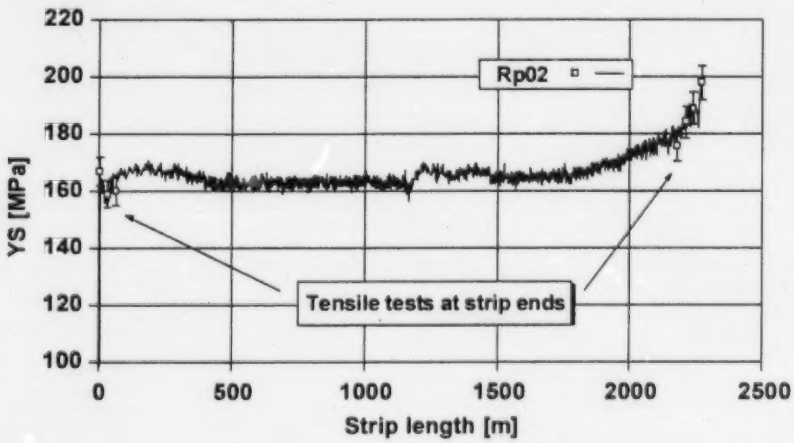


Figure 9: Continuous online measurements of yield strength at Thyssen Steel using a noncontact magnetic sensor [20]. Tensile tests at the ends of the coil show good agreement with the online sensor. Reproduced with permission.

using magnetic and ultrasonic techniques [19, 20]. The mechanical properties of interest are mainly yield and tensile strength as well as plastic strain ratio, r, (which relates to formability). Work has been underway for a number of years at the Institute for Nondestructive Testing in Saarbrucken and a prototype was tested for over a year on a production line at Thyssen Steel [20]. The sensor uses EMATS to propagate SH waves at 0 and 45° to the rolling direction of the sheet from which texture information and r-values are obtained. A second sensor uses a magnetic yoke, which applies a magnetic field to the sheet at 50 Hz while an eddy current coil senses changes in magnetic permeability. Yield strength is then correlated with features in the permeability curves. On-line measurements of yield strength are shown in figure 9. Comparison with mechanical tests at each end of the coil shows good agreement with the nondestructive sensor.

Another project for nondestructively measuring mechanical properties of steel sheet is also ongoing at the Industrial Materials Institute. In this case the measurement is entirely

based on laser-ultrasonics, i.e. a laser is used to generate the ultrasound and an optical interferometer is used for detection [21]. Ultrasonic attenuation is used to measure grain size and through thickness velocities of longitudinal and shear waves are used to obtain texture and plastic strain ratio. These velocities are deduced by analyzing the frequency spectrum over a period of ~ 40 microseconds, which corresponds to approximately 120 through-thickness round trips [22]. Resonances are observed which correspond mainly to longitudinal waves but also shear waves, which result from mode conversion. A prototype was installed at LTV Steel in Cleveland and is shown schematically in figure 10. Tensile and yield strength and r-values are obtained by correlations with attenuation and velocity parameters. Figure 11 shows online measurements of r-value measured along the length of a coil. The long-range variations, having a periodicity of ~ 1000 feet (~300m), were observed in several coils and appear to be associated with the process and not the particular product, thus providing an opportunity to correct the process.

MICROSTRUCTURE:

The laser ultrasonic prototype shown in figure 10 can also be used to measure variations in microstructure across the width of a flat product. Figure 12 shows variations of ultrasonic attenuation across the width of a hot rolled sheet (measured off-line) which reflect variations of grain size as confirmed by metallography. The difference in grain size near the edges is associated with the fact that edges underwent a different thermomechanical treatment. The measurements could be used to either reject part of the sheet or to modify the process.

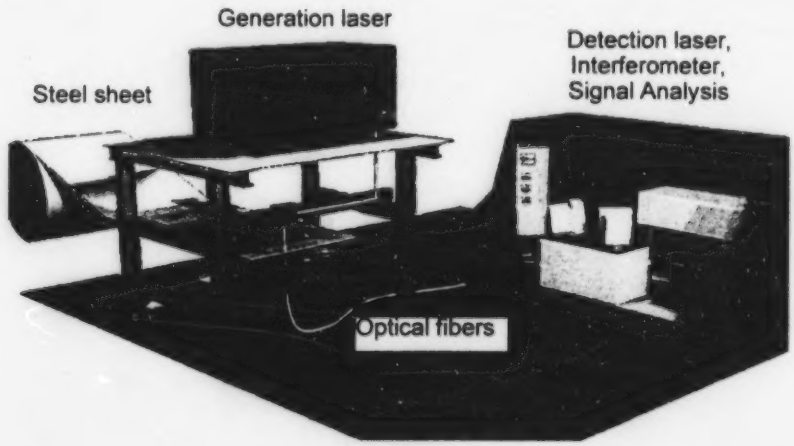


Figure 10: Schematic of laser ultrasonic prototype for online measurement of the mechanical properties of sheet steel as presently installed at LTV Steel in Cleveland Ohio.

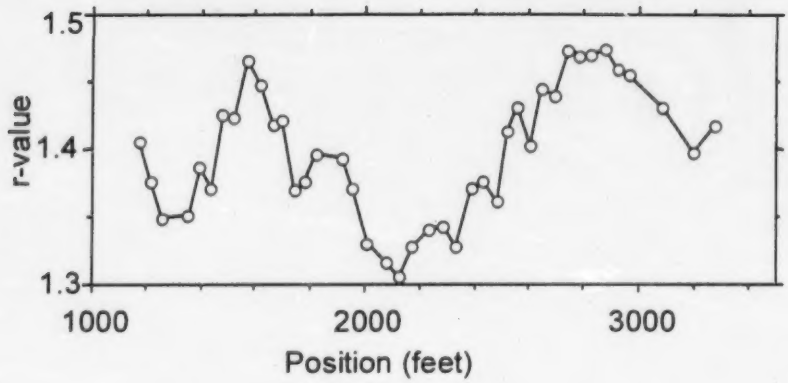


Figure 11: Variation of average r value as measured on line on a low carbon steel sheet using the laser-ultrasonic prototype shown in Figure 10.

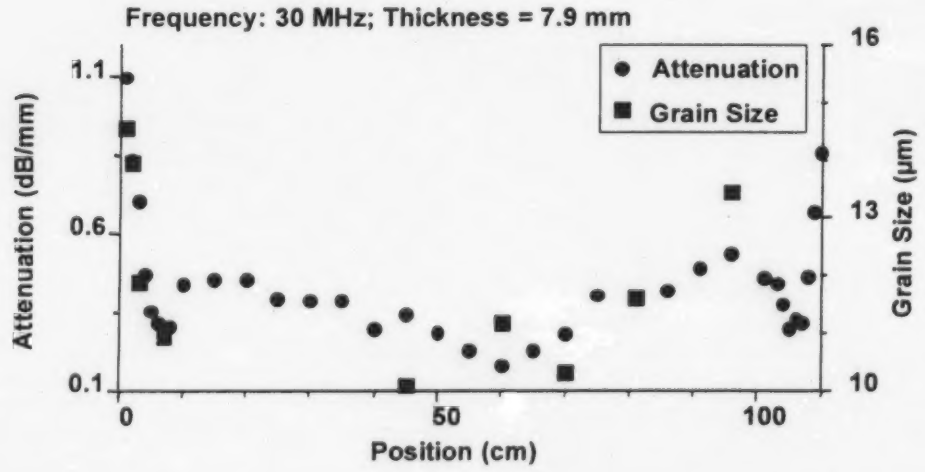


Figure 12: Ultrasonic attenuation measurements across a 7.9 mm thick hot rolled sheet and grain size as measured metallographically. Rapid increase of attenuation and grain size near the edges is associated with a difference in thermomechanical processing in this area. See ref [23].

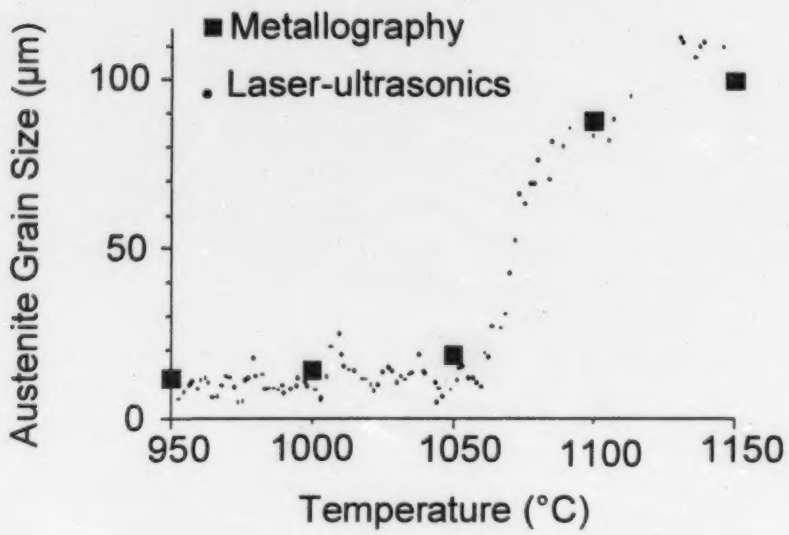


Figure 13: Austenite grain size evolution in a low carbon steel during a heat treatment of 5°C/s as measured by laser-ultrasonics and metallography. Metallographic measurements required the use of several samples that were quenched and analyzed at room temperature. Laser ultrasonic measurements are obtained in real-time on a single sample.

Nondestructive measurements can also be used to monitor microstructure evolution either during processing for process control or offline in the laboratory to better understand the relation between processing parameters and microstructure. Because of its noncontact nature, laser-ultrasonics offers good potential for monitoring the kinetics of microstructure evolution in real time [24]. Figure 13 shows measurements of grain size evolution as observed in a furnace during heat treatment at 1100°C. The rapid rise in grain size at ~ 1060°C is associated with the dissolution of AlN particles which act as pinning centers for the grain boundaries. Metallographic measurements are shown to agree with laser-ultrasonics. However they are very time consuming as each point on the graph requires a different sample which is heat-treated, quenched and examined by optical microscopy. Laser-ultrasonic measurements are obtained in real time allowing the possibility to follow changes in microstructure for complex treatments in real time, an opportunity for speeding up process development.

MATERIAL BEHAVIOR:

As a last example of a sensor for materials processing I will shift away from the primary metals industry and consider thermally sprayed coatings that are by far the most widely used in industry for the application of engineering coatings. They are, among other applications, commonly used for thermal barriers in the aerospace industry, corrosion resistant coatings in the paper industry and because of recent developments may soon be used in the average car to coat bored cylinders of aluminum blocks with a thin layer of steel for wear resistance.

The thermal spray processes involve producing molten particles that are projected onto a substrate where they solidify and build up a coating and include such processes as plasma spray, High velocity oxy fuel (HVOF) and others. Here we concentrate on plasma spraying whereby ceramic or metal powders are injected in a torch where they are heated by a plasma and accelerated by a gas. In such a process the structure and properties of the coating will depend on the state of the particles just before they reach the substrate. However, present state-of-the-art technology is based on the control of torch process parameters such as arc current and voltage, arc gas flowrate, powder feedrate, powder carrier gas flowrate and net plasma energy. These parameters are indirect and significant variations in coating properties can occur because process parameters are insensitive to such things as electrode wear and small variations between torches even for a given model and manufacturer. For control purposes, measurement of particle parameters such as size, speed and temperature before they impact the substrate should provide a closer link to coating properties.

A simple robust sensor was recently developed and commercialized at our institute for this purpose. It is basically a passive optical system which measures temperature (typically 1500-3500°C), size (typical range 10-100um) and velocity (~100-600 m/s) of the particles in flight. A small tubular (2.5x7.5 cm) fiber optic coupled head is placed near the particle jet shown in figure 14. The first element is a lens that images the light from particles travelling in the focal plane on the end of an optical fiber bundle. A linear fiber array provides the intensity profile of the spray plume across a 4-cm field of view. The central fiber of the array has a larger diameter (400 microns) and is covered with a two-slit mask (see right hand side of figure 14) and produces two-peak signals whose spacing in time is directly related to the velocity. In addition, the signal from the central fiber is also fed to a fast two-color pyrometer for temperature measurement. Particle diameter is estimated from the absolute intensity of the radiation and the measured temperature of the particle [27].

Use of the sensor both in the laboratory and in production environments has shown that torches of the same make and model can have significant differences not observable by an experienced operator, based on the readings of his instrument, such as a 50% difference in efficiency [26] and variation of particle temperature with time [27]. An example of temperature profile of the jet of zirconia particles for a thermal barrier coating after 1 hour and after 37 h is shown in figure 15. It is seen that a drop of more than 200°C is observed after the end of the 37-hr experiment. During this time, the velocity distribution also varied by more than 30 m/s out of approximately 200 m/s (~15%) leading to significant changes in microstructure [28]. However, by changing process parameters to recover particle parameters such as velocity and temperature, it was possible to reobtain the initial microstructure. Without the sensor the operator would have no idea as to how to modify torch parameters to recover initial conditions and microstructure. Integration of such a sensor in production will therefore provide new control strategies leading to much more reproducible and reliable coatings.

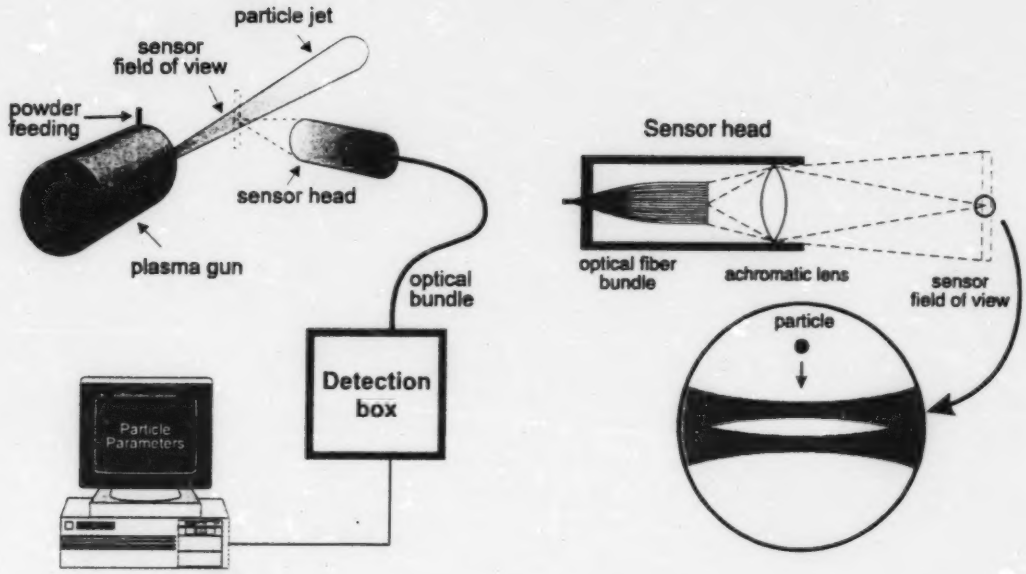


Figure 14: Optical sensor for monitoring particle parameters during plasma spraying. The sensor head (left) detects the radiation from the hot-sprayed particles to obtain particle size, temperature, and velocity as well as the global orientation of the beam. A central fiber in the sensor head is coated with a two-slit mask producing a split field of view near the focal point of the lens, which results in a double peak as a particle traverses it. The double peaked signals are used for velocity measurements. Reference [26]

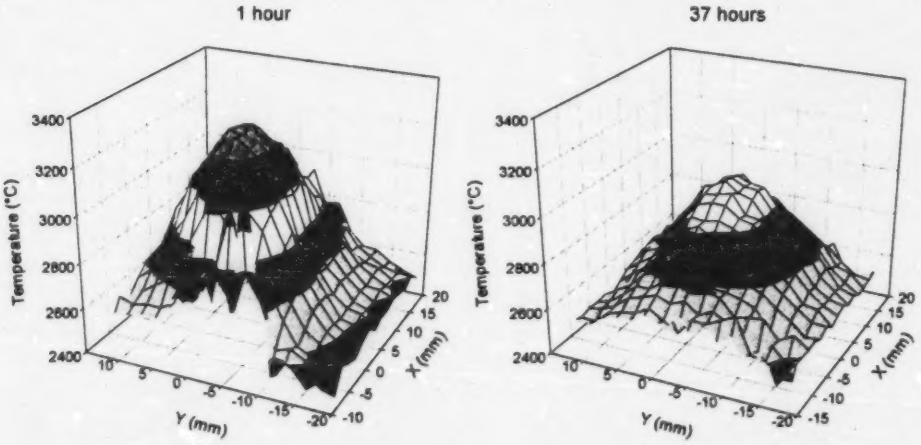


Figure 15: Temperature distribution of the particles at ~ 8 cm from the exit of the torch (normal projection distance) after 1h and 37 h of spraying zirconia for a thermal barrier application. After 37 hours the temperature has decreased substantially leading to important changes in microstucture which was later recovered by changing process parameters to obtain initial values of particle temperature and velocity. See ref [28].

CONCLUSION:

Most processing systems today are still automated based on process parameters such as temperature, pressure, flow rates, etc. which are controlled according to predetermined models and do not take into consideration the behavior of the material. However, the concept of Intelligent processing of materials, initiated more than fifteen years ago for more efficiently producing low volume advanced materials, has the potential for increasing productivity of common materials produced by the billions of dollars or billions of pounds such as steel, aluminum and chemicals and is gaining interest in these process industries because of environmental and economic pressures . With the availability of cheap computing power, the weak link towards implementation of these concepts will be the availability of cost effective, robust sensors which are sensitive to materials properties and behavior during processing. Such sensors are actively being developed in numerous laboratories around the world and are already leading to substantial increases in productivity. To illustrate these developments, examples of recent in-process sensors which measure chemical composition, temperature, microstructure and materials behavior in often difficult or harsh conditions of production environments were presented with indications of their benefits. These developments, however, represent only a small fraction of the needs and unmet needs should provide considerable opportunities and challenges for the NDE community.

Appendix F - List of Participants

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The group

Predictions for future manufacturing:

- The use of lubricants will disappear-dry processing will be introduced
- Die machining will be the norm
- Intrinsic material properties will eliminate the need for painting and plating
- Fixtureless assembly
- Haxapods
- Tissue engineering
- Materials – for hydrogen economy
- Production prototyping
- Rapid heating /cooling systems: microwave, HF induction, EM
- Self-contained man. proc.
- Electrochem. tech.: for hydrogen econ.
- Process integrat.
- Miiaturisation
- Materials to manage nuclear proc., waste
- Photonics e.g. laser proc.
- Nanomechanics
- Supercoductivity + superc. mat.
- Separat. tech.: membranes, bioprocessing
- Biological assembly: nanotech.
- Fuel cells
- Electrolyser systems
- Knowledge-based tech. – IT based, HS computing
- Light wt. mat.: Mg, Al, polymers
- Cogeneration techs. for htg/elec.
- Intelligent systems – electrical distribution
- Innovation management
- Combustion techs.